Impact of Sea Spray on the Balance of Turbulent Kinetic Energy in the Hurricane Surface Boundary Layer

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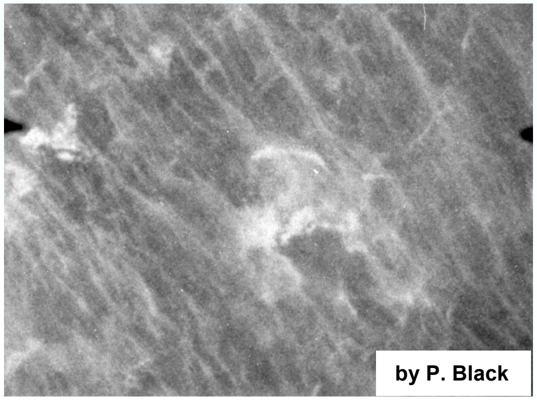
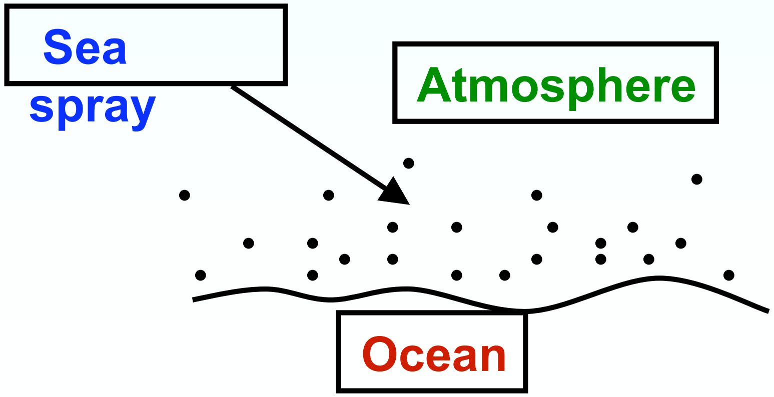
Presented at
The 1st NOA Testbed USWRP Workshop
Boulder, CO, April 29, 2009

Outline

- A Two-Phase Flow Problem
  - *Thermal effects: release of sensible and latent heat*
  - *Mechanical effects: suspension against gravitation*
- 1-D Modeling of Equilibrium SBL Flow
  - *Balance of turbulent kinetic energy (TKE)*
- Parameterization in NWP Models
  - *Extension of the Monin-Obukhov similarity theory*
- Summary of the HWRF Model Testing

Ocean surface whitecaps and foam streaks in a hurricane at wind speeds of ~46 m/s





1-D Spray–Laden Atmospheric Boundary Layer Model (Kepert, Fairall and Bao, 1999)

$$
\begin{cases}
\dfrac{\partial u}{\partial t} = -\dfrac{\partial}{\partial z}\left\langle u' w' \right\rangle - \dfrac{\partial}{\partial z}\left\langle u' w' \right\rangle_{sp} \\
\dfrac{\partial \vartheta_v}{\partial t} = -\dfrac{\partial}{\partial z}\left\langle \vartheta_v' w' \right\rangle - \dfrac{\partial}{\partial z}\left\langle \vartheta_v' w' \right\rangle_{sp} \\
\dfrac{\partial q}{\partial t} = -\dfrac{\partial}{\partial z}\left\langle q' w' \right\rangle - \dfrac{\partial}{\partial z}\left\langle q' w' \right\rangle_{sp} \\
\dfrac{\partial n}{\partial t} = - v_{\mathrm{fall}} \dfrac{\partial \mathrm{n}}{\partial \mathrm{z}} + \dfrac{\partial}{\partial \mathrm{z}}\left(\mathrm{K_D} \dfrac{\partial \mathrm{n}}{\partial \mathrm{z}} \right) - \dfrac{\partial}{\partial \mathrm{r}}\left(\dfrac{\partial \mathrm{r}}{\partial \mathrm{t}} \mathrm{n} \right) + \mathrm{S}
\end{cases}
$$

where n is the droplet number density of radius r and salt mass m_s, the x axis is parallel to the horizontal component of the wind u, ϑ_v is the virtual potential temperature, ρ is the total density of the droplets-fluid mixture, c_p is the specific heat at constant pressure, q is the specific humidity, and z is the height, K_D is the droplet diffusivity, and S is the droplet source function.

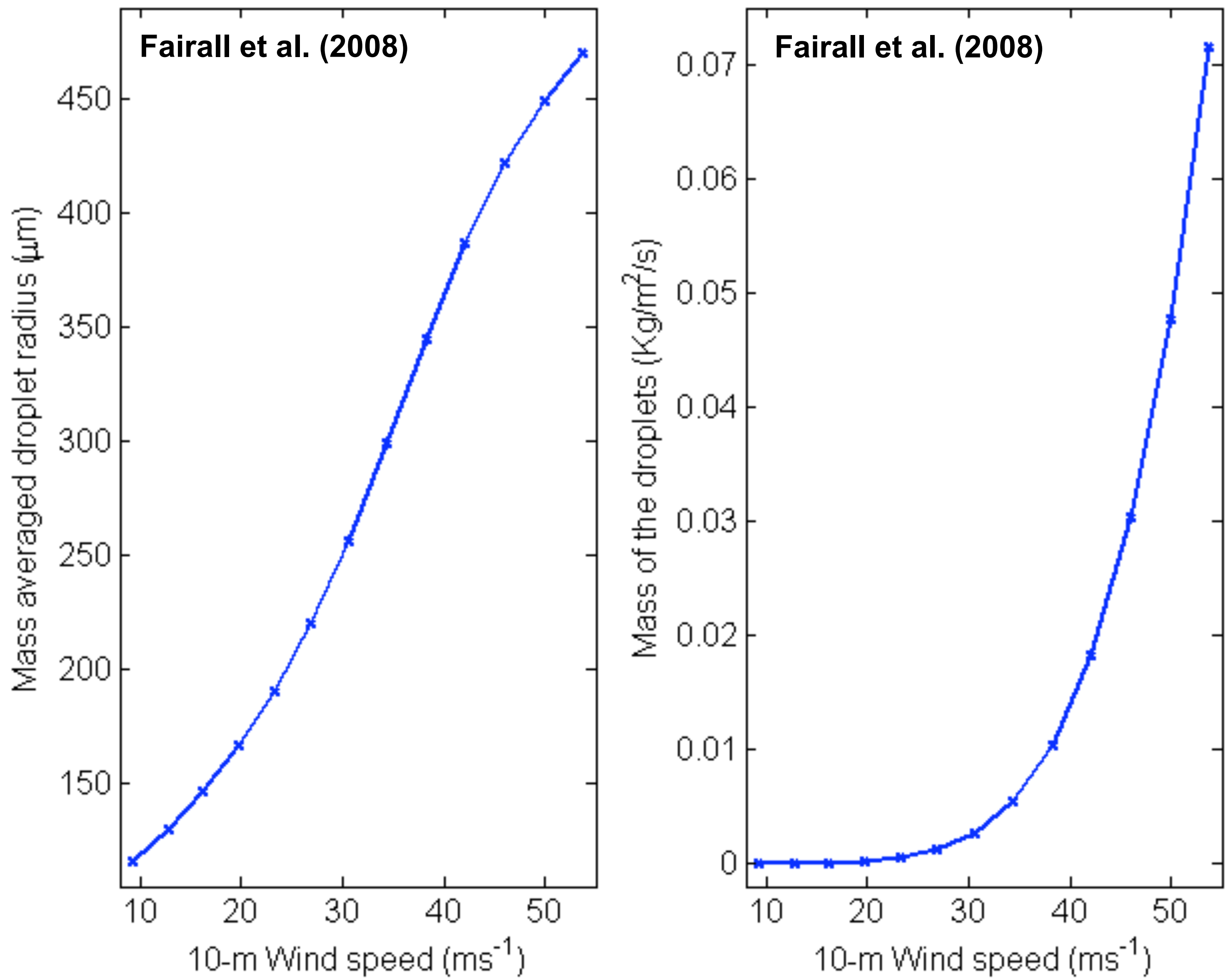
Turbulence Model

sea spray mediated buoyancy production and dissipation

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right) = -\langle u'w'\rangle \frac{\partial U}{\partial z} + \left(\frac{g\langle \theta_v' w'\rangle}{\Theta} + \frac{g\langle \theta_v' w'\rangle_{sp}}{\Theta}\right) - \left(\varepsilon + g\sigma V_f S\right)$$

where z is the vertical coordinate, $\langle\ \rangle$ denotes mean (following the Reynolds convention), q^2 is twice the TKE, U is the mean horizontal velocity of air motion, u' and w' are the eddy components of U and the vertical air motion, Θ and θ are the mean and eddy components of potential temperature, ε is the dissipation rate of TKE, and g is the acceleration of gravity, $\langle\ \rangle_{SP}$ is the turbulent flux mediated by sea spray, $\sigma = (\rho_{sp} - \rho)/\rho$ is the relative excess of the density of sea water ρ_{sp} over the density of air, V_f is the fall speed of sea spay droplets, and S is the volumetric concentration of sea spray mass.

Left: Mass averaged droplet radius as a function of the 10-m wind speed.
Right: Mass of the droplets as a function of the 10-m wind speed



Diagnosis of Sea Spray Effects in Terms of the M-O Similarity Theory

$$\frac{\partial}{\partial t}\left(\frac{q^2}{2}\right) = -u_*\left(\frac{\partial u}{\partial z}\right) + \beta g\overline{w'\vartheta_v'} - \varepsilon' = -u_*\frac{\partial u}{\partial z}\left(1 - \frac{\beta g\overline{w'\vartheta_v'}}{u_*\frac{\partial u}{\partial z}}\right) - \varepsilon' = 0$$

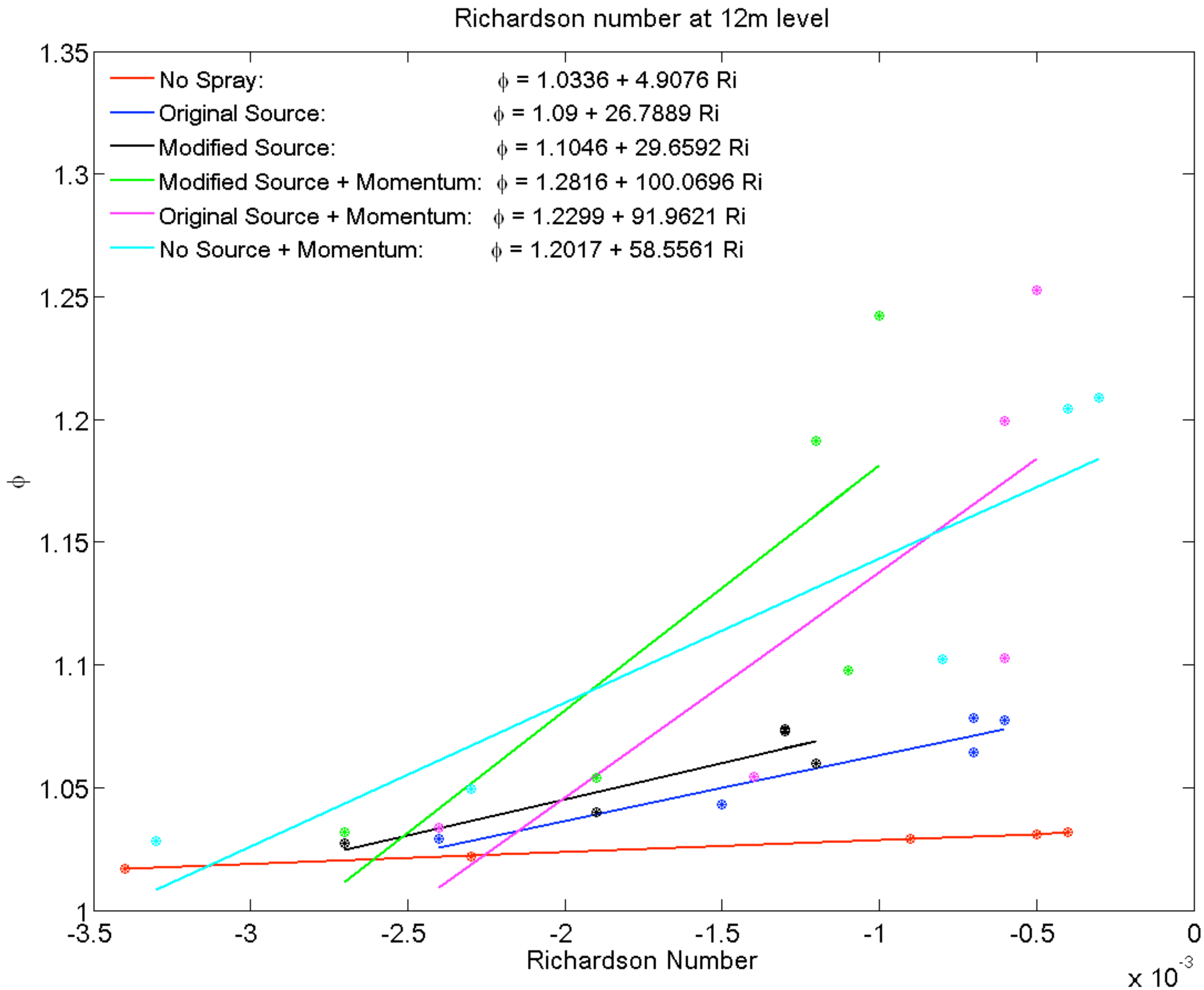
$$\varepsilon' = \varepsilon + \sigma V_f S g = \left[\frac{1}{B_1} + \sigma V_f S g \frac{l}{q^3}\right]\frac{q^3}{l}$$

$$L^{-1} = -\frac{kg\overline{\vartheta_v' w'}}{\vartheta_v u_*} + \frac{\sigma \overline{S' w'}}{u_*^3}$$

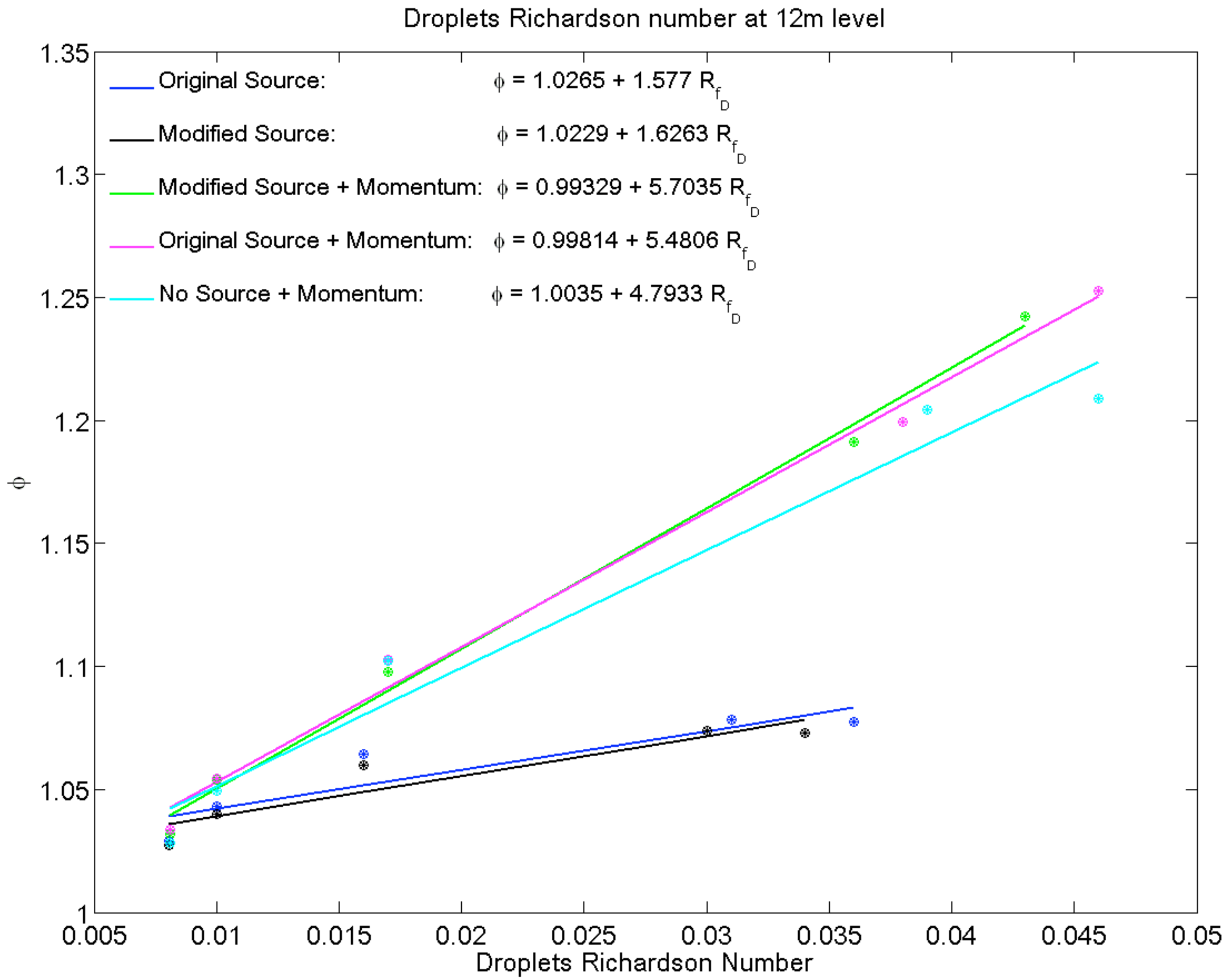
$$\frac{kz}{u_*}\frac{\partial u}{\partial z} = 1 + R_{f_{TOT}} = \phi\left(\frac{z}{L}\right)$$

$$R_{f_{TOT}} = \frac{z}{L} = -\frac{kgz\overline{\vartheta_v' w'}}{\vartheta_v u_*^3} + \frac{\sigma z\overline{S' w'}}{u_*^3} = R_f + R_{f_D}$$

Flux Richardson Number at 12 M



Droplet Richardson Number at 12 M



Summary of the Sea-Spay Physics

- The suspension of sea-spray droplets reduces the buoyancy and makes the surface layer more stable, reducing the friction velocity and the downward turbulent mixing of momentum.

- Sea-spray droplets tend to cool and moisten the surface boundary layer at winds below 35 ms^{-1} , but they tend to warm and moisten the surface boundary layer at winds above 50 ms^{-1}.

- The sign of the flux Richardson number is opposite to the droplet Richardson number at hurricane-strength winds.

- The effect of the flux Richardson number is smaller than that of the droplet Richardson number at hurricane-strength winds, rendering the overall effect of sea-spray to be that the vertical mixing of both momentum and heat are enhanced.

The NOAA/ESRL Parameterization Scheme of Sea Spray in the HWRF Model

- A physical model of sea-spray generation function consistent with wave breaking dynamics

- An extension of the Monin-Obukhov similarity framework to take into account the feedback effects

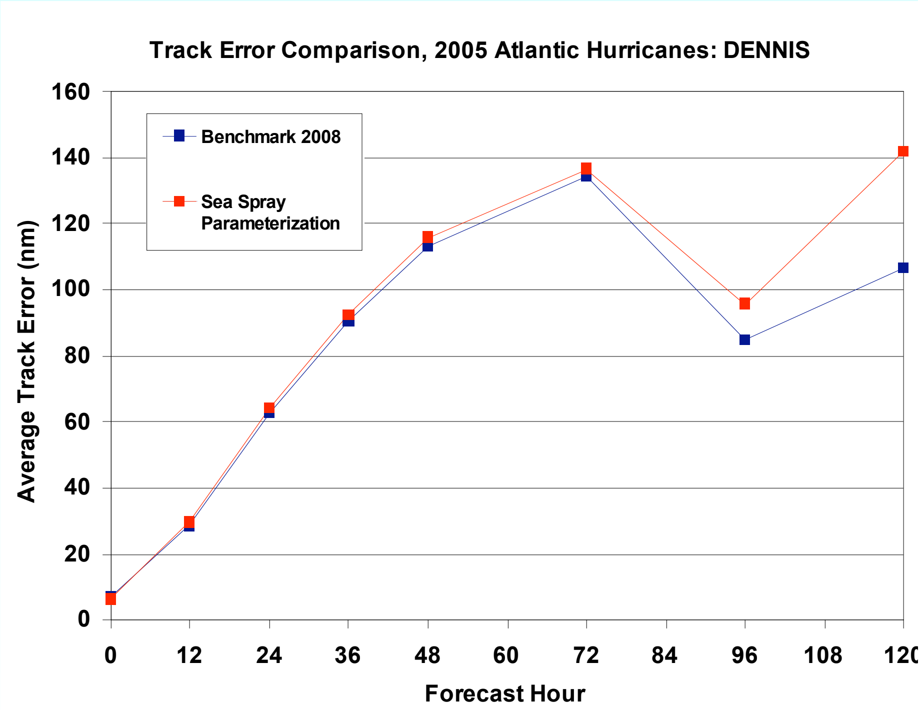
$$u_* = \frac{\kappa(U - U_0)}{ln(z/z_0) + \Psi_m(z/L)}, \qquad \frac{-\left(\langle \theta w \rangle + \langle \theta_{sp} w \rangle\right)}{u_*} = \frac{\kappa(\Theta - \Theta_0)}{ln(z/z_0) + \Psi_h(z/L)}$$

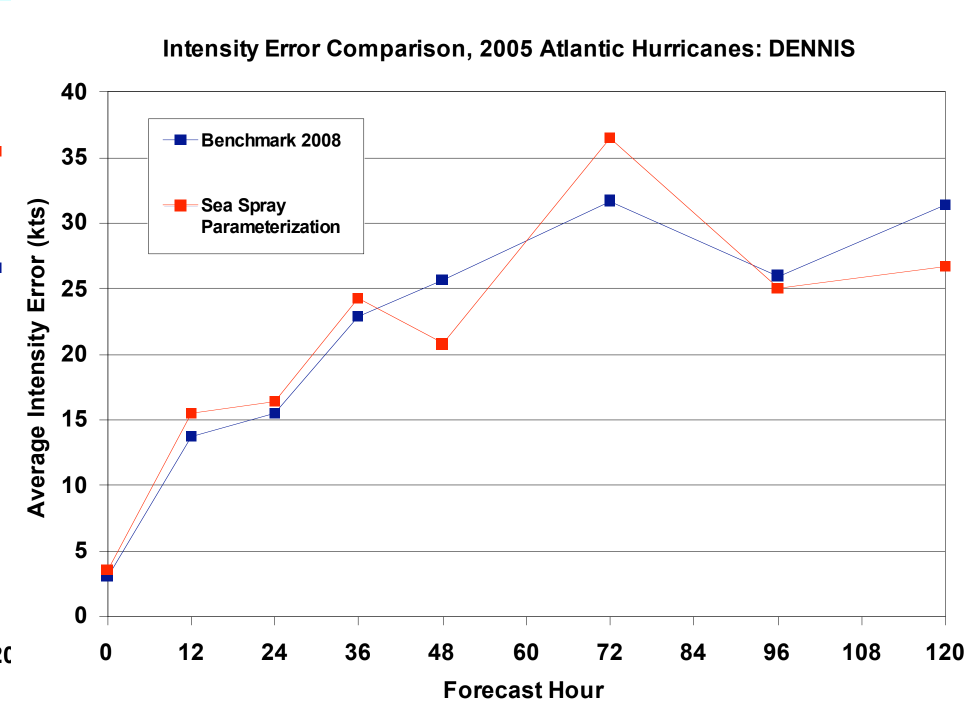
$$L^{-1} = -\frac{kg\overline{\vartheta_v' w'}}{\vartheta_v u_*} + \frac{\sigma \overline{S' w'}}{u_*^3} = L_{MO}^{-1} + L_{SP}^{-1}$$

$$\Psi_m(z/L) = \Psi_{m1}(z/L_{MO}) + \Psi_{m2}(z/L_{SP})$$

$$\Psi_h(z/L) = \Psi_{h1}(z/L_{MO}) + \Psi_{h2}(z/L_{SP})$$

HWRF Evaluation: Dennis (2005)





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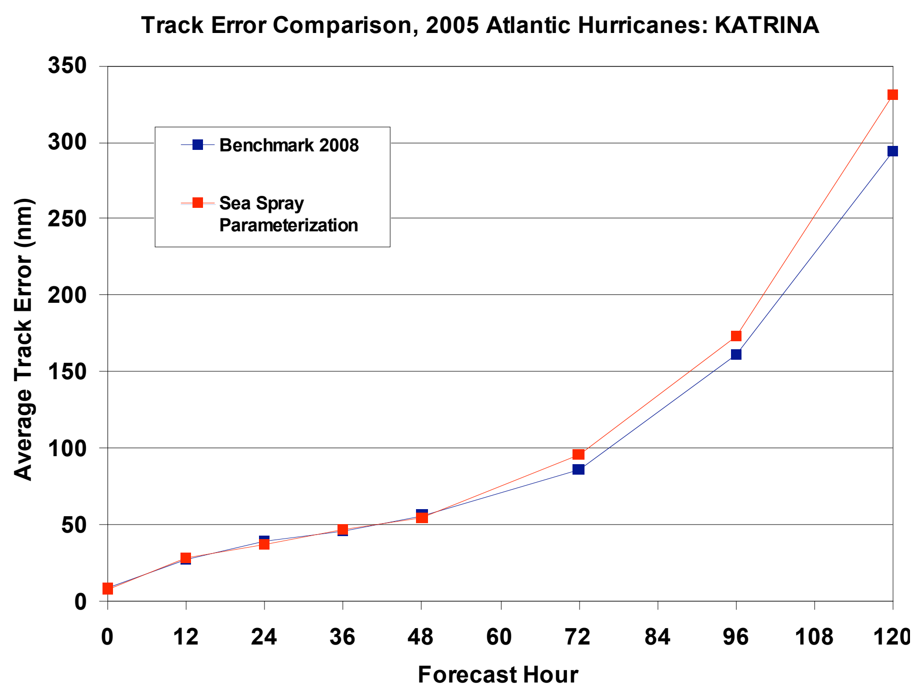
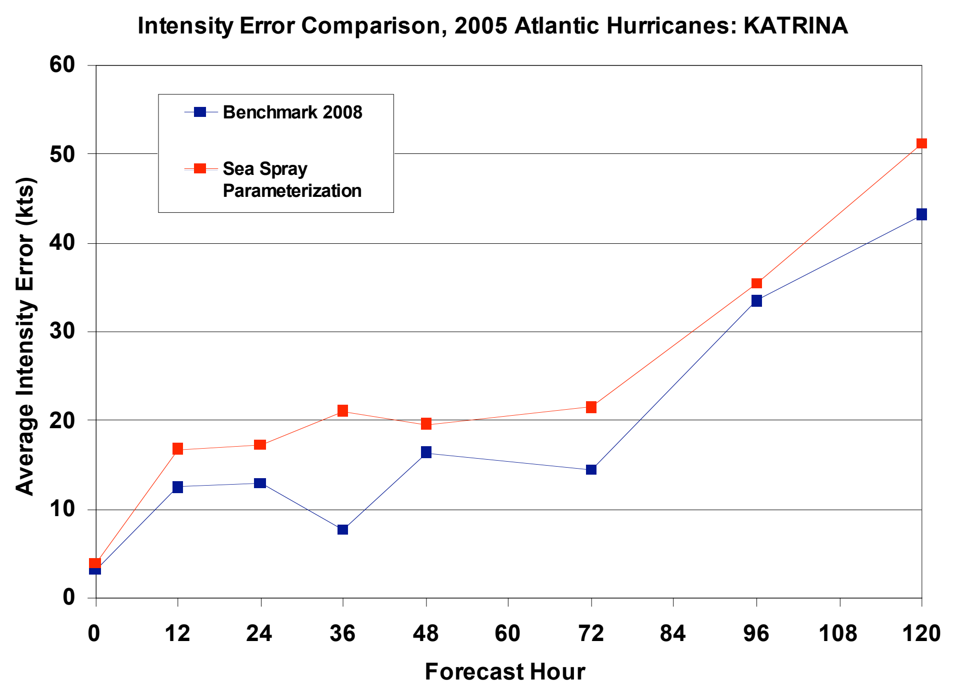
HWRF Evaluation: Katrina (2005)





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Summary of the HWRF Testing

- For strong storms (such as Katrina and Rita), the scheme tends to produce a greater positive bias of intensity during the first 48-72 hours than the control runs, while the impact on track is negligible.
- For weak storms (such as Dennis), the scheme tends to produce an intensity bias that varies around that of the control runs, while the track is degraded slightly after 72 hours.
- The storm structure is affected by the sea-spray mediated momentum and heat fluxes, suggesting a strong connection between the surface fluxes and the vortex dynamics through the convection in the eyewall (not shown).
- The performance of the scheme can be improved by tuning the source function and the degree of feedback effects.